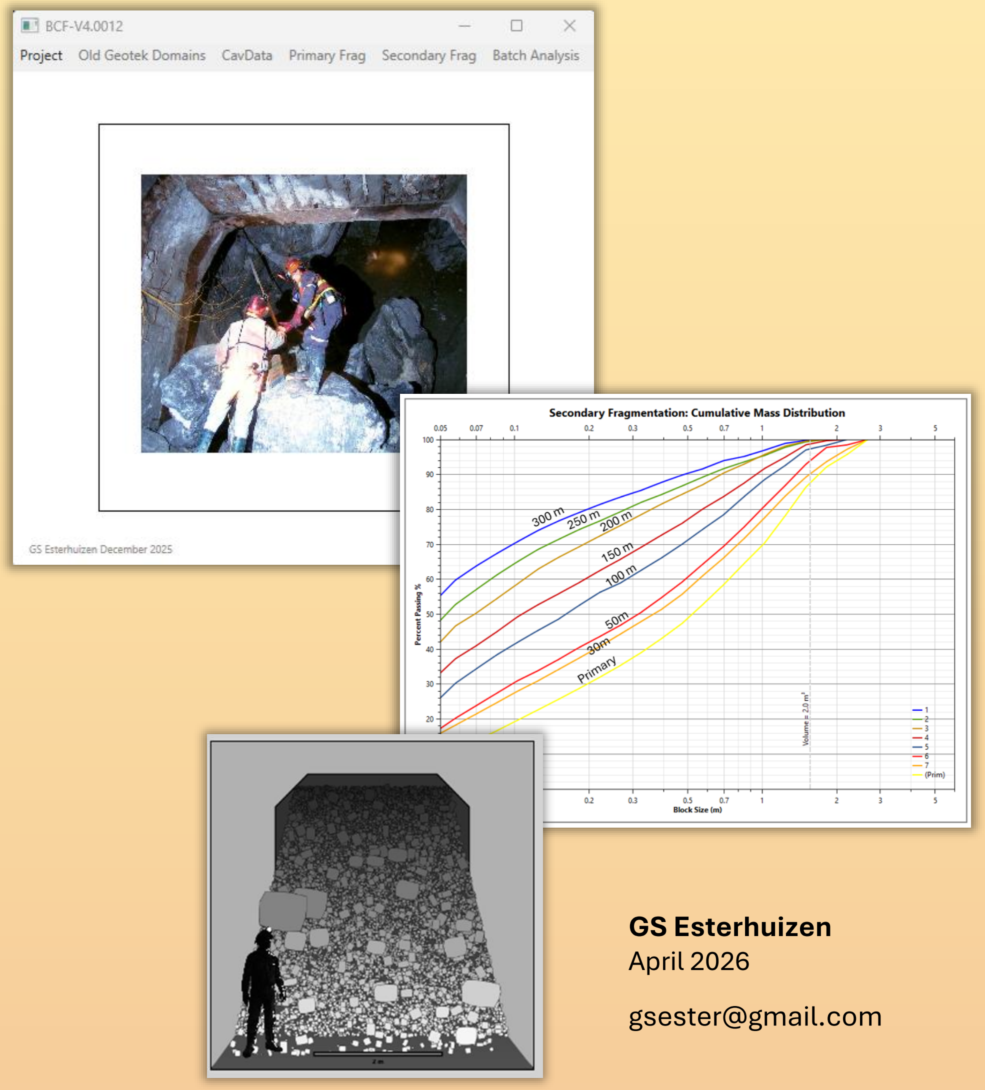
User’s Guide and Technical Reference
BCF V4



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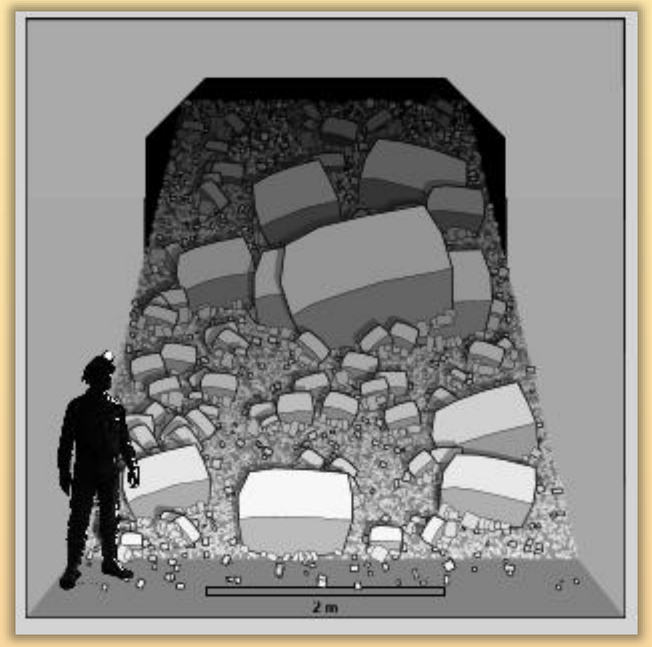


The BCF Approach

BCF is an empirical fragmentation assessment tool for block cave mining.

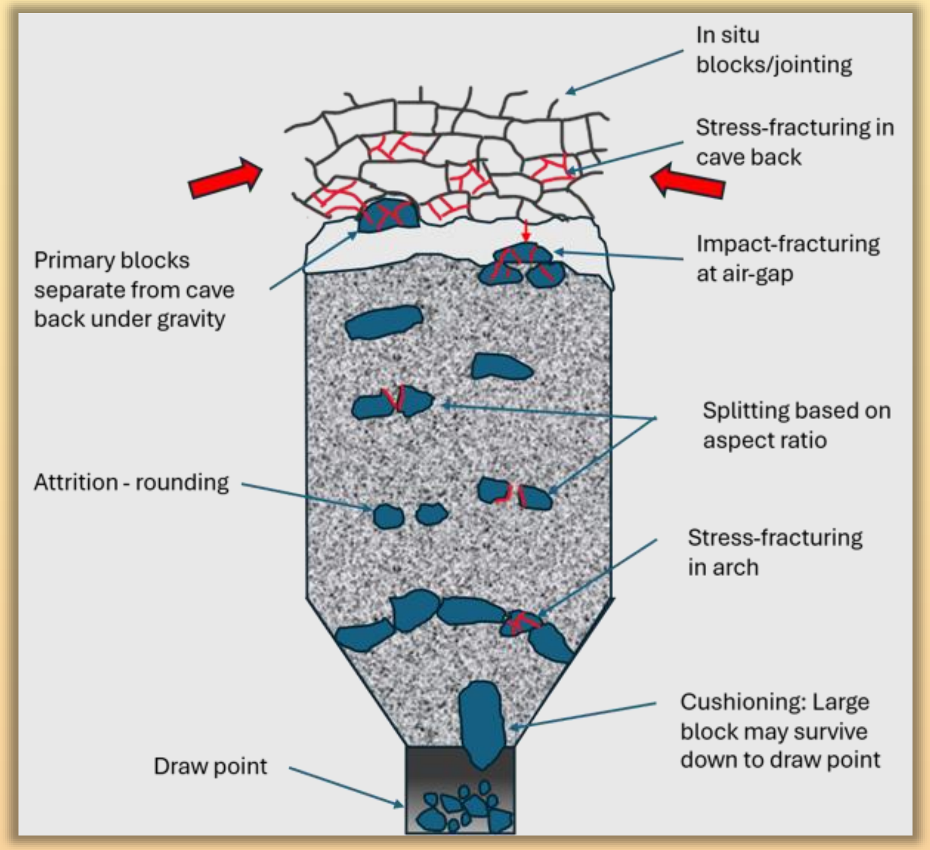
BCF is designed so that analyses can be conducted by geologists or geotechnical engineers at a mine site without the need for specialized numerical modeling skills. The analyses are easy to set up and run and provide results in a few seconds, allowing numerous alternatives to be evaluated efficiently.

The availability of fragmentation measurements made at operating mines over the past 20 years since BCFV3 was released has made it possible to improve the BCF method to better match fragmentation measurements. The updated BCFV4 remains an empirical fragmentation assessment tool based on observations, insight, rock engineering principles, and engineering judgement.

Types of Fragmentation

In BCF the rock mass is assumed to be unfragmented prior to mining. Fragmentation of the rock mass occurs when the rock mass separates into blocks that are bounded by fractures such as joints, weak veins or stress fractures. In cave mining the separation of the rock mass into rock blocks is typically driven by gravity or stress fracturing. The following types of blocks are defined:

- In situ rock blocks: Blocks that can potentially separate along natural surfaces prior to caving. Actual separation of the rock mass into fragments will depend on stress conditions, shear strength and orientation of fracture planes.
- Primary fragments: Rock blocks formed by separation from the rock mass under gravity. This process is called "Primary Fragmentation"
- Secondary fragments: Caved rock blocks in the draw column of the cave operation. These rock blocks may reduce in size as they fall onto the top of the draw column, and as they are drawn down to the drawpoints by attrition, splitting, stress fracturing, shearing along internal defects etc. These processes are all part of "Secondary Fragmentation"



Input Data Needed

To use BCF it is first necessary to collect geotechnical data of the orebody that will be caved. The orebody can generally be subdivided into domains of similar geotechnical characteristics. The Laubscher-Jakubec Mining Rock Mass Rating system (2001) is used as a basis for classifying the rock mass. This system adequately addresses items such as veining/weathering/small- and large-scale block strength. Sufficient inputs can be gathered from drill core only, which is essential for feasibility or early design before the orebody has been exposed in mine development.

Information is needed about the ground stress in which the cave will operate. Stress measurements or published information about ground stress in the mining region can be used. Numerical models can be built to obtain more detailed stress-estimates of planned extraction sequences.

Basic mine design information is needed about the likely size of the cave panel, drawpoint dimensions and height of draw.

Significant updates in BCFV4 from BCF V3

Primary fragmentation

- Block disintegration under cave-back stress loading was changed to produce a wider range of fragment sizes. Parallel stress fracture planes are no longer assumed.
- Veins within a rock block affect the fragmentation size distribution and may separate to form a block.
- In-situ block accretion criteria modified to better match observations.
- Fines from shear zones, core-loss zones, and stress-fracturing are better accounted for.

Secondary Fragmentation

- Secondary block failure mechanisms of splitting, compressive failure, and attrition (block rounding) have been significantly modified to better match measured single block fragmentation in laboratory testing and through validation against case studies of fragmentation measurements in cave mining operations.
- Fines production from block failure and attrition were modified to better match observations.
- The impact of ingress of small fragments from above the draw zone can be assessed.
- Fragmentation from free-fall of primary fragments through an air-gap can be assesses (experimental).

BCF-V4 Primary Fragmentation Input data

Primary fragmentation data and analysis is based on the Laubscher-Jakubec (2001) approach to rock mass rating and accounting for the presence of healed veins within the rock mass. The data inputs are subdivided as follows:

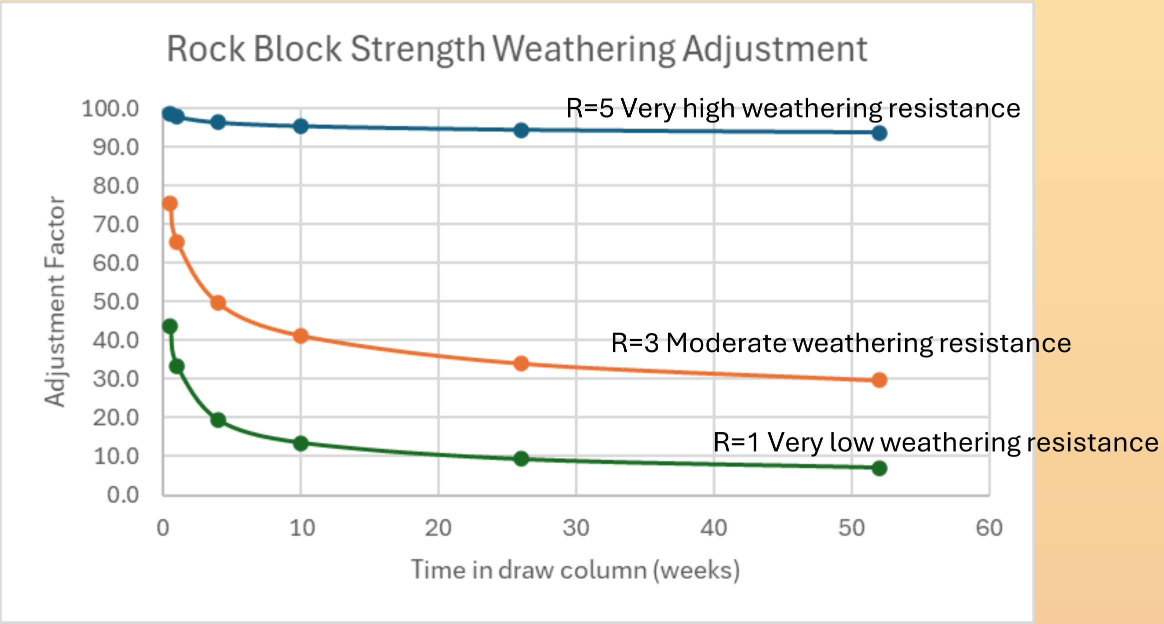
Rock strength parameters:

- **UCS** (Uniaxial compressive strength) of standard 50mm diameter rock samples in MPa. If micro veins are present in the samples the UCS should include the effect of micro veins. Larger veins (meso-veins) that are not present in the UCS samples are accounted for separately
- **Vein frequency:** Large widely spaced meso-veins that are not present in the 50 mm samples. Frequency per meter. This would typically vary from about 5 or 10 per meter to 0.1 per meter etc. More than 10 per meter would likely be included in the 50 mm sample UCS.
- **Vein strength:** Use Moh's hardness scale according to Laubscher and Jakubec (2001) with the likely range between 1 and 5. Hardness > 5 will likely be equal to the intact rock strength and have no impact on rock block strength. Veins with Hardness 1 or 2 will likely act as weak joints and should rather be entered as a random joint set. BCF will assign approximate cohesion and friction angle based on Hormazabal and Russo vein shear testing results.

BCF-V4 Primary Fragmentation Input data

- **Rock weathering resistance rating**: A parameter describing the rate of weathering of the rock once it is exposed to moisture and air within the draw column. A scale of 1 to 5 is used with 1 = very low weathering resistance and 5 is very high resistance. Using the Laubscher and Jakubec weathering adjustment *W* the Weathering resistance rating (*WRR*) can be calculated approximately as: WRR = 0.057 x W – 0.71. Note that even very strong rocks like granite will lose some strength when saturated in water. BCF will apply a small strength reduction even for the strongest rocks. No weathering is assumed to occur during primary fragmentation.

- The **degree of weathering** depends on the time the rock blocks are resident in the draw column during secondary fragmentation. An exponential strength decay function is applied to account for strength reduction with time. The time spent in the draw column is dependent on the draw height and the rate of draw at the drawpoint. For example: A weathering resistance rating of 1 will reduce the fresh rock-block strength by 30% after 1 week and will reduce it by 90% after 20 weeks in the draw column.



BCF-V4 Primary Fragmentation Input data

- **Rock block strength:** Strength of rock blocks in between block forming fractures (MPa). This should include the effect of meso-veins that are not present within UCS samples. RBS should be calculated using Laubscher & Jakubec (2001). User can enter the RBS manually or can click a “Calc” button in BCF that will calculate an approximate RBS of a 1 m-size rock block. The RBS is used to calculate the In-Situ RMR. It also provides the basic strength parameter controlling the block fragmentation under compressive stress and fragmentation during draw-down in the draw column.

- **In-Situ RMR:** The unadjusted IRMR determined according to Laubscher and Jakubec (2001). This is automatically calculated by BCF using inputs on the screen, including joint set characteristics. The BCF calculated IRMR may not agree with detailed IRMR values calculated for complex geology and jointing scenarios. You can overwrite the BCF calculated IRMR if you have calculated the IRMR separately. BCF uses whatever IRMR value is in the text box when you save or start the primary fragmentation analysis. The IRMR together with joint set spacing are used as a parameters affecting maximum block size during primary fragmentation.

- **MRMR:** This is the “Mining Rock Mass Rating” which is just the IRMR x W where W is the weathering adjustment. The MRMR is not directly used in BCF but is presented for info only.

BCF-V4 Primary Fragmentation Input data

Block Forming Fracture Data: Data for natural fractures/joints/bedding planes etc. that are not healed but are likely to separate under gravity during the caving process. This would include weakly cemented meso-veins the easily separate during core-drilling. Allowance is made to enter sets of joints as well as random oriented fractures.
In some case like porphyry orebodies there are no readily discernible joint sets and it is necessary to describe the jointing as “random”. BCF allows cases with “random jointing only” to be considered.

Fracture set data required:

- **Dip, StdvDip:** The mean dip and standard deviation for joint planes in each joint set in degrees (0 to 90 degrees)
- **DipDir, StDvDDir:** mean and standard deviation of dip direction of joint planes in degrees (0 to 360 degrees) North zero angles measured clockwise.
- **Mean/Min/Max Spacing**: spacings in (m) measured along a line perpendicular to the mean joint orientation (true spacing)
- **JCondition/Stdv:** mean and standard deviation of the joint condition (10 to 40) according to MRMR2001.

BCF-V4 Primary Fragmentation Input data

Random oriented fracture data:
Scattered joints that fall outside the regular joint sets can be added to the analysis. These are additional to the regular joint sets. The user must enter the average frequency and condition of the random joints.

Rock mass view to confirm joint data:
BCF can create a 3D view of the rock mass to show approximately what the defined joints look like.

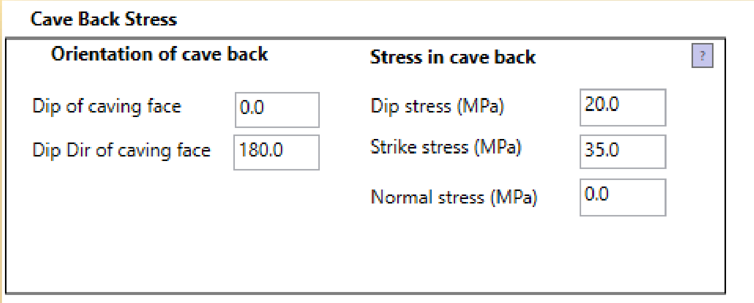
Verifying fracture frequencies from entered jointing data:
An option exists to calculate fracture frequencies in any direction through the defined rock mass. This is useful to compare your defined rock mass with fracture frequency observed in borehole drilled in the same direction.

BCF-V4 Primary Fragmentation Input data

- **Analysis with veins only:** If there are no readily identifiable open joints, but veins are present, a “veins only” analysis can be conducted. Veins are then treated as a random “cemented joint” set with friction and cohesion properties derived from the Moh-hardness number. The veins will form block boundaries just like a normal random joint set if the shear-stress or gravity load is sufficient to dislodge a block from the surrounding rock mass. Typically one would expect the Moh-hardness to be greater than 2 for a “veins only” case, because veins that have Moh-h <= 2 would probably be counted as open joints.

BCF-V4 Primary Fragmentation Input data

Cave back stress data



Cave Back Stress

Orientation of cave back

Dip of caving face: 0.0

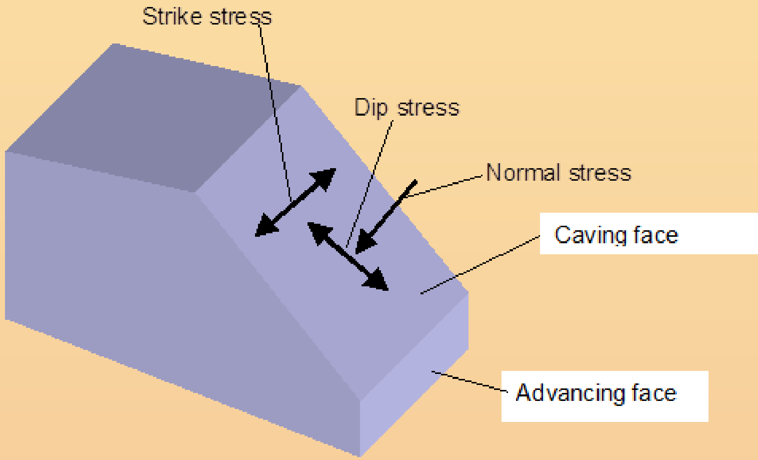
Dip Dir of caving face: 180.0

Stress in cave back

Dip stress (MPa): 20.0

Strike stress (MPa): 35.0

Normal stress (MPa): 0.0



Stress in the cave back can induce fracturing and shearing along natural structures in the rock mass. The stress near the caving face is likely to be higher than the far-field ground stress that exists before mining. The mining induced stress near the cave-back can be estimated from numerical models. In general one should assume that the stress normal to the caving face is zero because of the free face at the caving boundary. If all the stress components are non-zero the rock mass is unlikely to separate under gravity, and BCF may predict huge primary fragmentation blocks.

Stress in cave back: In BCF we simplify the stress condition by considering stress in the dip and strike directions of the caving face and setting the normal stress to zero. Stresses are compressive positive entered in MPa. The Normal stress should be set to zero.

Orientation of cave back: The orientation of the cave back can be horizontal for established cave panels when caving is progressing vertically. For advancing cave fronts, for example, the cave back may be entered as dip = 55 degrees and dipdir = direction of advance (0-360 degrees clockwise from North).

***Note:** If you set all the stress components to zero or negative BCF will assume that every joint surface will separate and will produce blocks similar to DFN analyses. This is an extreme case that is not used in BCF. In the normal situation where the dip and strike stresses are compressive, block accretion occurs which can form large blocks relative to the joint spacings, depending on stress orientation, joint conditions and overall rock mass strength.

BCF Primary Fragmentation Calculation

Formation of In-Situ Blocks

The in-situ rock blocks are assumed to be bounded by up to six joint surfaces selected from the defined joint sets. The selection of joints to form a block is based on the frequency of occurrence of the joints. More frequent joints will be selected for block formation more often than infrequent joints. The block dimensions are determined by the spacing of the joints, the shear strength along the joint surfaces and the tensile strength across the joint surfaces. Depending on the stress field, the joint may either shear and form a block surface or may be clamped. If joint surfaces are clamped, the tensile strength across the joint may hold the two surfaces together and form a larger block, called a combined block.

- *The joint condition:* a weak, planar joint is more likely to be continuous and will separate more easily than a strong joint;
- *Stress in the cave back:* the stress in the cave back can cause shear failure and separation of the joint;
- *The weight of the block:* Gravity driven separation or shearing along a joint surface is more likely in larger blocks than small blocks. The Insitu RMR is used as a parameter to limit the maximum block sizes

A number of empirically derived relationships are used in BCF to relate the probability of a joint separating to form a block face to the three above factors.

BCF Primary Fragmentation Calculation

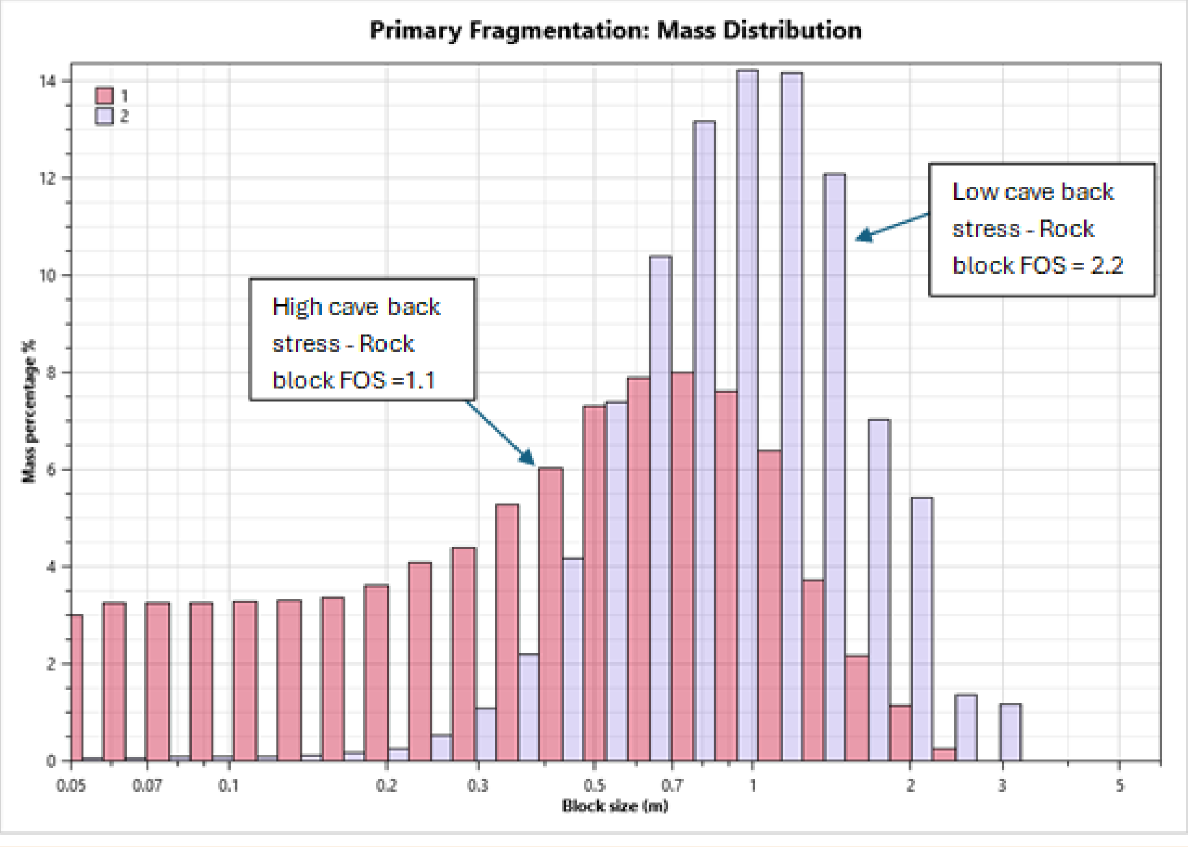
Fragmentation of In-Situ Blocks subject to Cave Back Stress

Fragmentation of in-situ blocks subject to cave back stress is now based on the concept of single block fragmentation. Observations of fragments in drawpoints, the results of laboratory tests, and numerical simulations show that when an intact rock block fails under compression, broken particles can be produced that have a wide range of sizes, ranging from less than 1 mm to a large fraction of the original rock block (Li and Elmo 2025, Pierce et al. 2010). In BCF-V4 the variability of the rock block strength is considered, and the blocks that are over-stressed are assumed to break up into a range of fragments with the maximum fragment volume stochastically assigned, ranging from 25% to 50% of the original block volume. A percentage of the volume is assumed to be fines, depending on the ratio of cave-back stress to block-strength. The remaining volume is stochastically distributed into fragments with volumes that lie between the maximum fragment size and the fines limit (5 cm block size). This approach better represents the breakup of a rock block that fails in a compressive stress environment. The resulting fragmentation is more representative of actual compressive stress failure when compared to the simple introduction of parallel stress fractures used in earlier versions of BCF.

BCF Primary Fragmentation Calculation

Fragmentation of In-Situ Blocks subject to Cave Back Stress

This figure shows an example of primary fragmentation block size distributions for a rock mass subject to low and moderately high cave-back stress. For the lower stress case the factor of safety (FOS) of rock blocks in the cave-back is 2.2, which does not cause any stress fracturing. In the higher stress case with FOS = 1.1, more than 50% of the blocks in the cave back fail and the size distribution of the fragments becomes spread out through the smaller size categories with about 30% of the fragments being classified as fines (< 5 cm).



Secondary Fragmentation in the Draw Column

Fines from block attrition

As rock blocks travel down the draw column, they move at different velocities and may tumble when they are at the border of a movement zone. The resulting attrition between rock blocks is assumed to produce fragments smaller than 5 cm and directly contributes to the fines volume. In BCF-V4 fines generation due to attrition is calculated using the rock block strength, which is affected by potential weathering and the presence of veins withing the block. Each time a block splits in the draw column, new “unrounded” corners are created which will further contribute to fines generation.

Secondary Fragmentation in the Draw Column

Block fragmentation from splitting and crushing

Block splitting due to point loading or bending when the block aspect ratio is large is the most common fragmentation mechanism considered by BCF. Splitting is also recognized as the primary mode of failure in granular materials (Mesri and Vardhanabhuti 2009; Pierce, Weatherley and Kojovic 2010). The occurrence of splitting is treated as a probabilistic event that depends on several factors, including: the aspect ratio of the block, the rock block strength, amount of fines in the draw column, and the cave pressure. The presence of fines acts as a cushion against point loading of a block, and will lower the probability that a block will split.

In BCF each of the parameters affecting splitting are evaluated at vertical intervals as a rock block travels down the draw column. When a block splits, the fragmentation products are tracked as they travel further down the draw column. The products may again split as the cave pressure increases or the rock block strength decreases due to weathering. The procedure described earlier for cave-back stress related failure is applied to determine the largest split fragment and the intermediate fragments larger than 5 cm. Fragments smaller than 5 cm are treated as fines.

The split-fragmentation parameters differ from the cave-back stress fragmentation parameters to account for the fact that block splitting under bending will produce larger fragments and less fines than crushing under multi-axial compression.

Secondary Fragmentation in the Draw Column

Crushing in the draw column

The probability for block crushing in the elevated stress conditions associated with arching in the draw column is evaluated using the same compressive failure procedure as that used for cave-back stress fragmentation. Arching related failure is affected by the cave pressure in the draw column, the block strength, including the potential impact of weathering.

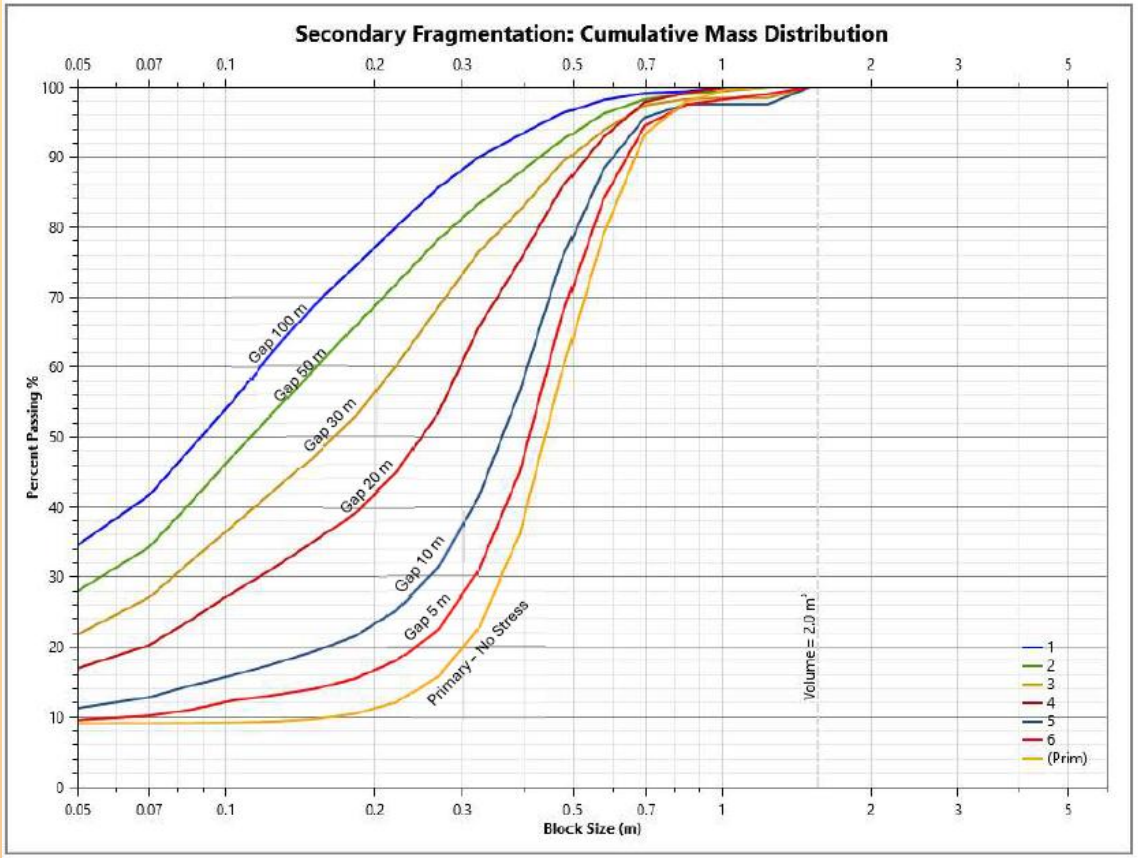
The figure in the next page presents an example of the various fragmentation processes that BCF-V4 applies to the primary fragments as the height of draw (HOD) increases. This set of results is for relatively strong rock mass with a rock block strength of 70 MPa. The results show that initial fracturing in the cave back and block splitting in the draw column are the main processes of block fragmentation, while about 35% of the fragmented material is produced by block attrition when the HOD is 300 m. As the height-of-draw increases, the attrition mechanism consumes a portion of the fragments that failed in the cave back and split in the draw column. When the height-of-draw is 300 m approximately 8% of the primary fragments arrive at the drawpoint unaffected by the splitting and crushing activity in the draw column.

Secondary Fragmentation in the Draw Column

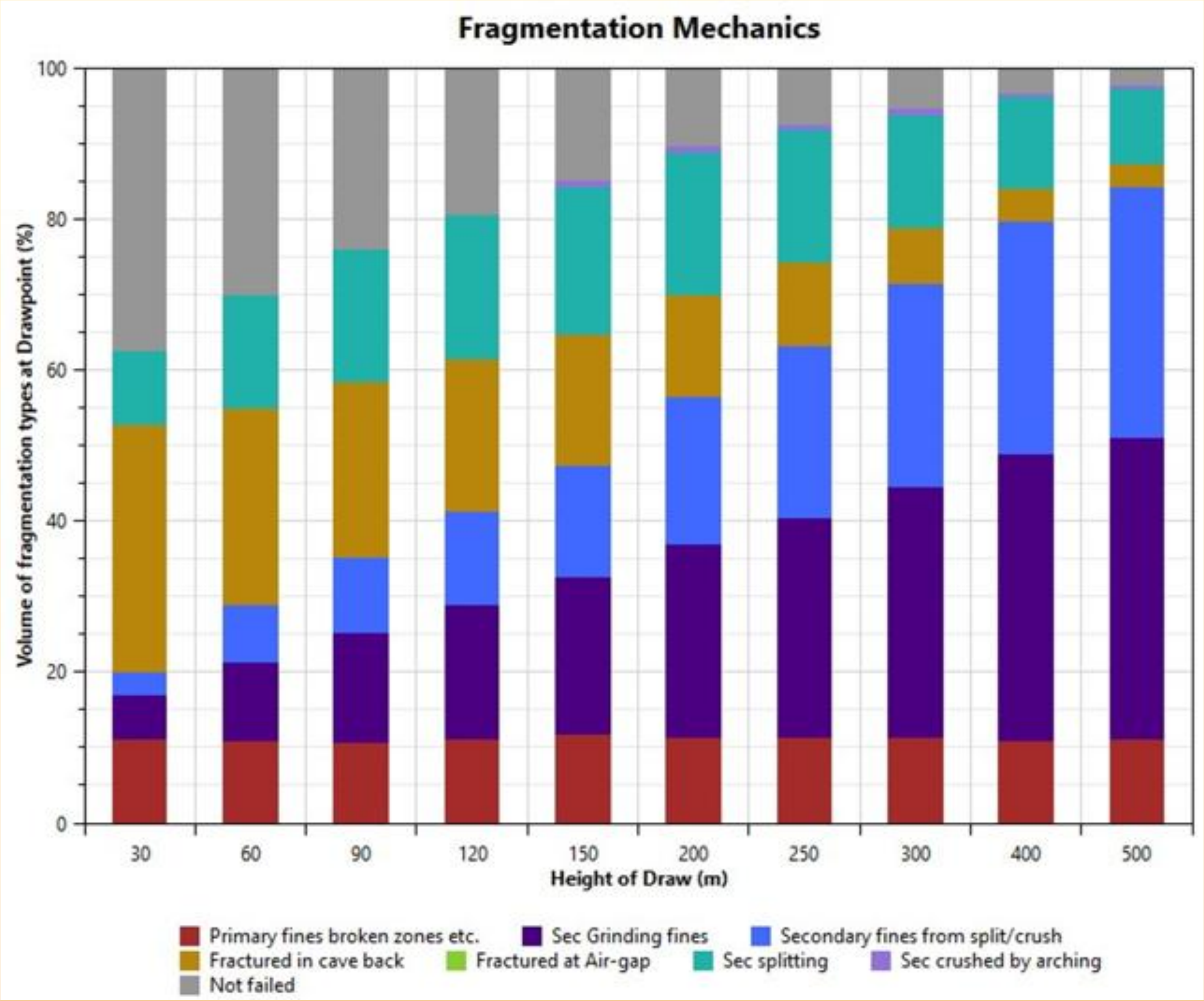
Air Gap: Impact Fragmentation

Specifying an air gap between the cave back and the top of the draw column will simulate fracturing of primary blocks when they impact the broken rocks of the draw column . The approach used is to consider the kinetic energy of the block relative to its cross-sectional area and the block strength. Fracturing is coarse because of the high-energy impact, and it produces less fines than fracturing under low energy conditions during draw-down. Example results below:

Effect of air gap only – Size distribution at top of draw column after falling through air gap



Secondary Fragmentation in the Draw Column

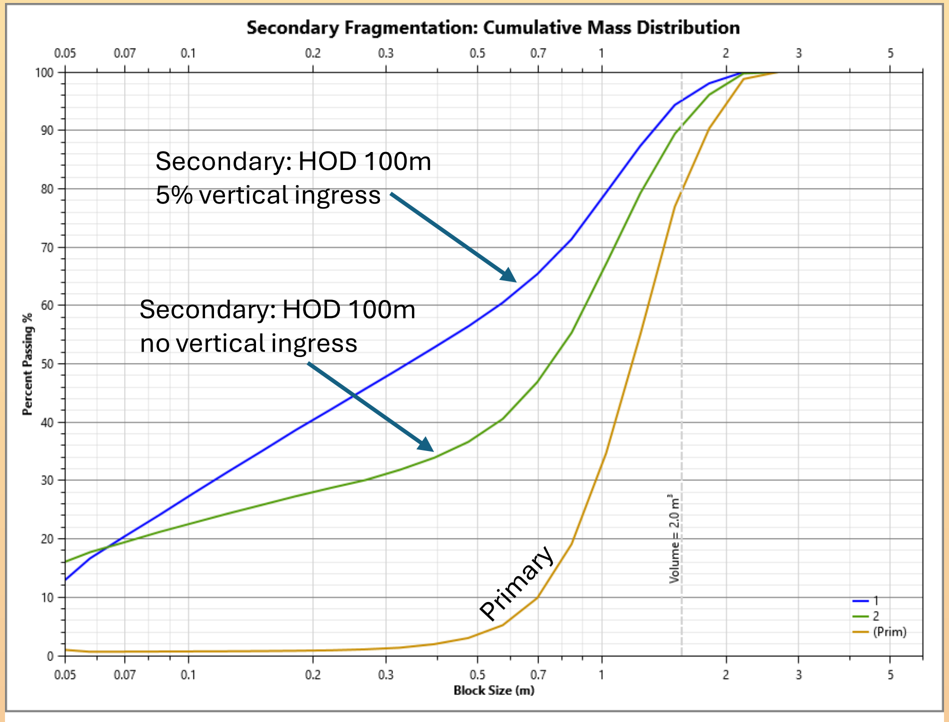


Example showing role of various failure mechanics as the height of draw increases from 30 m to 500m

Secondary Fragmentation in the Draw Column

Vertical Ingress

The vertical Ingress parameter tries to simulate the fact that smaller blocks travel down the draw column faster than larger blocks. This can help to explain why observed fragment size distributions do not always follow a nice s-shaped curve as predicted by numerical simulations. In BCF V4 it is possible to specify a percentage “ingress” which adds additional smaller blocks to a calculated fragmentation curve. About 5% “ingress” seems to be reasonable. However, it is not necessary to specify “ingress” because reasonable fragmentation curves can be achieved using the current block-fragmentation algorithms in BCF V4.



Secondary: HOD 100m
5% vertical ingress

Secondary: HOD 100m
no vertical ingress

Primary

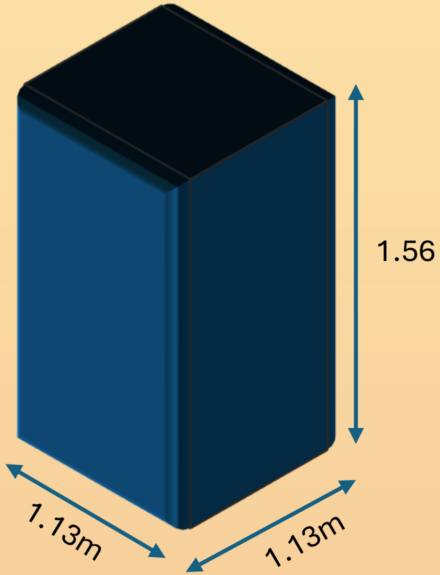
Linear block size:

Reporting fragment size as “block volumes” is not as intuitive as a linear dimension. Sieve analysis traditionally presents sizes as linear sieve dimensions. BCF fragmentation results are now presented as a “linear” size calculated as the diameter of an equivalent sphere with the same volume:

$$\text{Size} = \sqrt[3]{6V/\pi}$$

For example: 2m^3 has an equivalent size of 1.56m. Assuming the block is prism-shaped its dimensions would be 1.56 x 1.13 x 1.13 m.

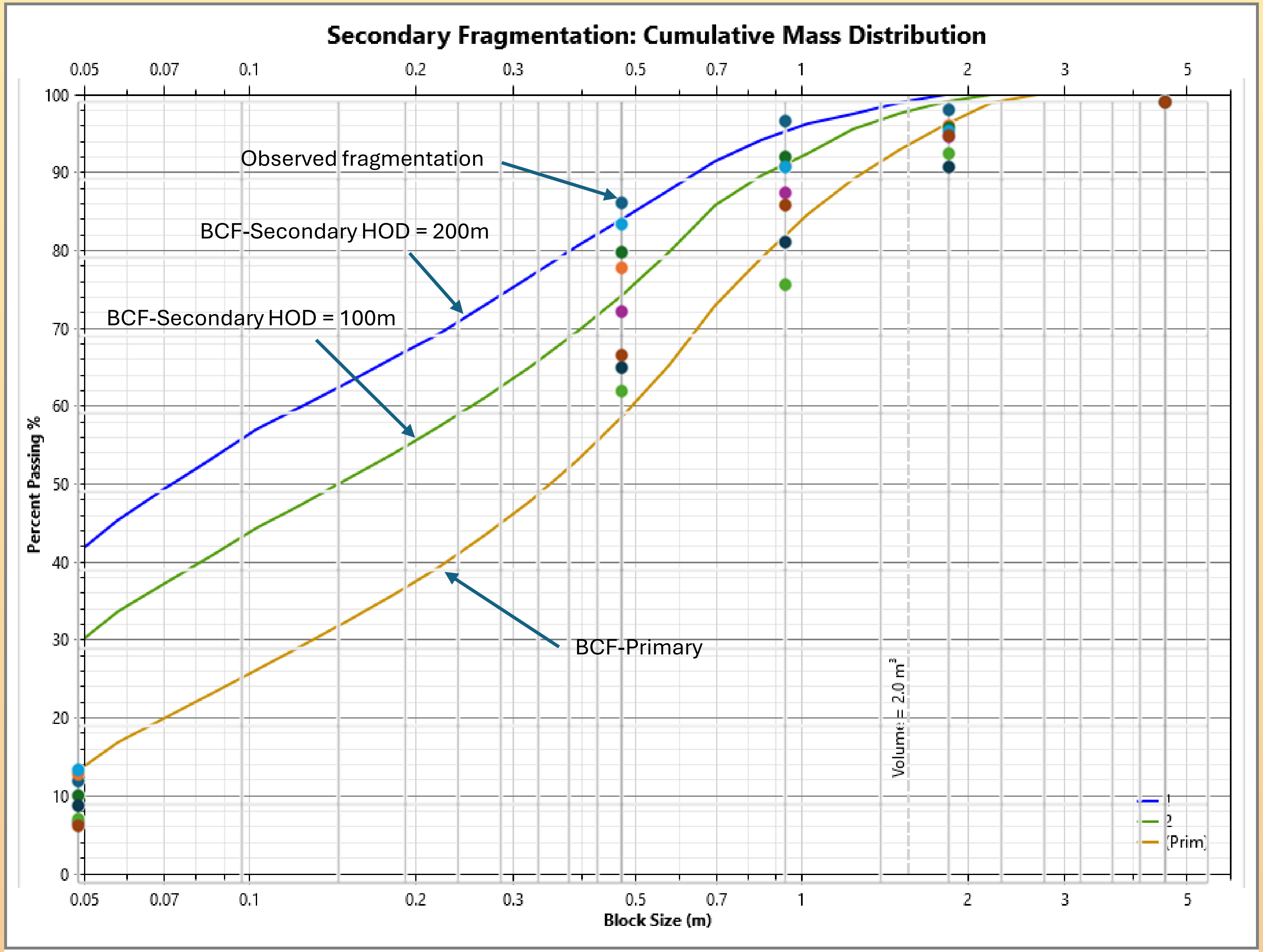
A 2m^3 block



Fine materials in BCF

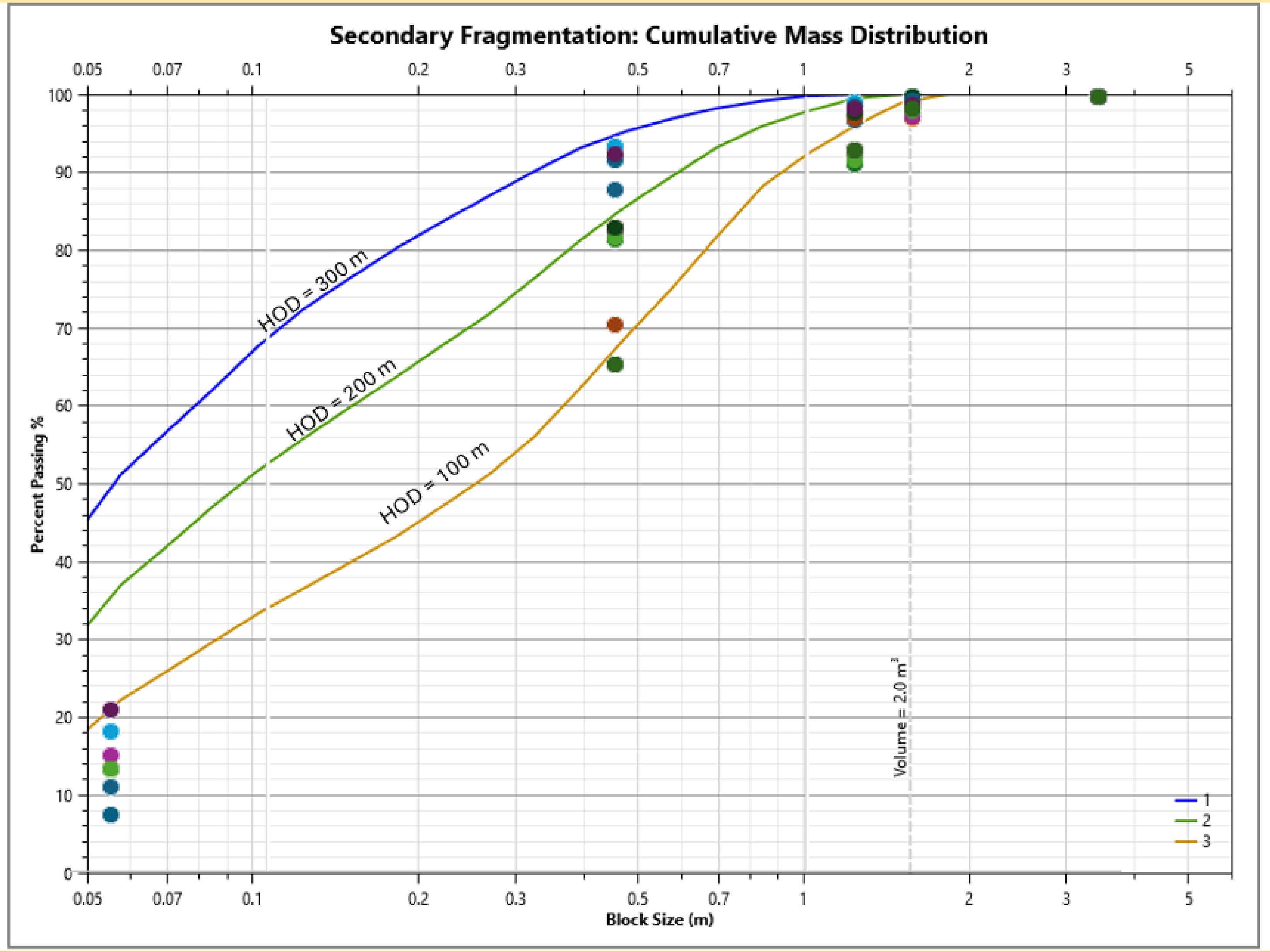
In BCF-V4 fine materials are simply treated as the volume of particles that are less than 5 cm in size, aligning with industry practices, without attempting to classify them into smaller sizes. Fragments larger than 5 cm are individually accounted for in BCF and are reported in the fragmentation size distribution. The in-situ rock mass typically contains fine materials which exist prior to mining. These fine materials may include broken particles in brecciated zones, finely ground particles in shear zones, intrusion related particles such as small-scale veinlets or block defining veins. In BCF-V4 these pre-existing fine materials are defined by specifying the percentage of broken or rubble-core or otherwise observed fault-shear and brecciated zones.

Example 1: Porphyry deposit 100m-200m HOD, Visual observations of fragmentation vs. BCF V4



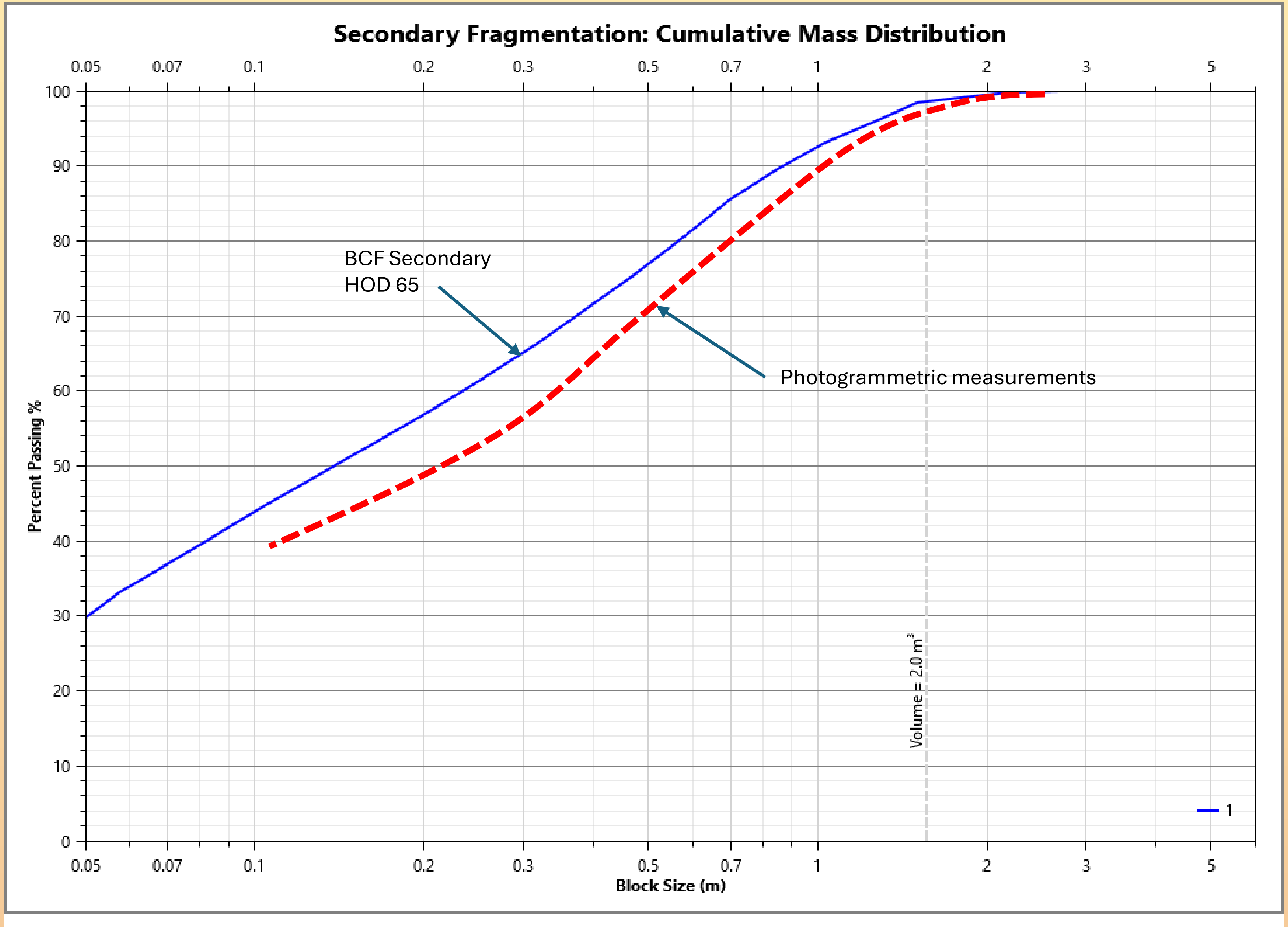
BCF fragmentation analysis using random jointing and available rockmass/stress parameters. Each dot represents average fragmentation of around 100 draw-points. It is likely that visual estimates underestimated the fines.

Example 2: Porphyry deposit HOD 100 – 300 m, Visual observations of fragmentation vs. BCF V4



BCF fragmentation analysis using Geotech data from feasibility study. Visual observations of fragmentation likely underestimated fines.

Example 3: Porphyry deposit HOD 55 - 75m, Visual observations of fragmentation vs. BCF V4



BCF fragmentation analysis using geotech and stress data data from feasibility study. Note: Geotech engineers added 30% fines to measurements because of fines hidden by larger blocks in drawpoint